



**QUEEN'S  
UNIVERSITY  
BELFAST**

## **Cross-layer Framework for Fine-grained Channel Access in Next Generation High-density WiFi Networks**

Zhao, H., Zhang, S., & Garcia-Palacios, F. (2016). Cross-layer Framework for Fine-grained Channel Access in Next Generation High-density WiFi Networks. *China Communications (IEEE)*, 13(2), 55-67.  
<https://doi.org/10.1109/CC.2016.7405725>

**Published in:**  
China Communications (IEEE)

**Document Version:**  
Peer reviewed version

**Queen's University Belfast - Research Portal:**  
[Link to publication record in Queen's University Belfast Research Portal](#)

### **Publisher rights**

© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works

### **General rights**

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

### **Take down policy**

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact [openaccess@qub.ac.uk](mailto:openaccess@qub.ac.uk).

# Cross-layer Framework for Fine-grained Channel Access in Next Generation High-density WiFi Networks

Haitao Zhao<sup>1\*</sup>, Shaojie Zhang<sup>1</sup> and Emiliano Garcia-Palacios<sup>2</sup>

<sup>1</sup>College of Electronic Science and Engineering, National University of Defense Technology, 410073, Changsha, China

Email: [{haitaozhao, zhangshaojie}@nudt.edu.cn](mailto:{haitaozhao, zhangshaojie}@nudt.edu.cn)

<sup>2</sup>ECIT Institute, Queen's University Belfast, BT3 9DT, Belfast, U.K

Email: [e.garcia@qub.ac.uk](mailto:e.garcia@qub.ac.uk)

\* Corresponding author: [haitaozhao@nudt.edu.cn](mailto:haitaozhao@nudt.edu.cn); Tel.: +86 (0)731 84575703

**Abstract:** Densely deployed WiFi networks will play a crucial role in providing the capacity for next generation mobile internet. However, due to increasing interference, overlapped channels in WiFi networks and throughput efficiency degradation, densely deployed WiFi networks is not a guarantee to obtain higher throughput. An emergent challenge is how to efficiently utilize scarce spectrum resources, by matching physical layer resources to traffic demand. In this aspect, access control allocation strategies play a pivotal role but remain too coarse-grained. As a solution, this research proposes a flexible framework for fine-grained channel width adaptation and multi-channel access in WiFi networks. This approach, named SFCA (Sub-carrier Fine-grained Channel Access), adopts DOFDM (Discontinuous Orthogonal Frequency Division Multiplexing) at the PHY layer. It allocates the frequency resource with a sub-carrier granularity, which facilitates the channel width adaptation for multi-channel access and thus brings more flexibility and higher frequency efficiency. The MAC layer uses a frequency-time domain backoff scheme, which combines the popular time-domain BEB scheme with a frequency-domain backoff to decrease access collision, resulting in higher access probability for the contending nodes. SFCA is compared with FICA (an established access scheme) showing significant outperformance. Finally we present results for next generation 802.11ac WiFi networks.

**Keywords**—Channel width adaptation, Multi-channel access, High-density WiFi

## 1. Introduction

### 1.1. High-density WiFi: Problem statement

With mobile traffic exploding and video traffic growing at an incredibly fast rate, the challenge of how to fill a growing bandwidth gap has been widely acknowledged in the industrial and research community. Although in recent years the infrastructure in 3G and 4G mobile networks has been greatly enhanced, cellular networks alone cannot meet this demand. WiFi seems to be the natural port of call for closing the bandwidth gap. Many are proposing

an integration between cellular and WiFi technologies that allow users to tap into the much higher bandwidth provided by WiFi. Smart aggregation and segregation of traffic and smart allocation of applications could be used to optimize resources and to off load traffic from cellular networks. The integration of WiFi seems to be a popular one due to easy deployment and low cost, having the added benefit of increased capacity. With the evolution towards 5G in cellular and next generation WiFi networks (IEEE 802.11ac/ad) this tendency is bound to continue. Densely deployed WiFi APs are therefore an important trend to be considered.

Despite more WiFi APs appearing to be the obvious solution, this is not a guarantee for end users obtaining higher throughput. There is on one hand the problem of increasing interference among end users and overlapped WiFi channels. On the other hand, the intense contention for the shared spectrum resources constitutes an added difficulty resulting in increased collision and backoffs, which quickly decreases throughput and network efficiency. To aggravate these problems, existing medium access control (MAC) schemes are too coarse grained when allocating resources at the physical layer. As it will be shown in this research, as physical data rates increase the efficiency gets even worse! The fundamental reason for this is that current MAC schemes allocate the entire physical channel to one station as a single resource at a time, which does not necessarily match individual traffic demands, so as wider channels are used the inefficiencies increase. For example, the latest ratified 802.11n [1] and IEEE 802.11-2012 [2] standard improves the maximum data rate up to 600Mbps, while the data throughput efficiency (i.e the ratio between the network throughput and the PHY data rate) in an 802.11n network could be as low as 20% [3]. In next generation WiFi networks (802.11 ac/ad) throughput efficiency could be less than 10% [5].

A MAC scheme which allocates the entire channel to a single user, even if there is only a small amount of data that needs to be sent, is far from ideal. Let's not forget that this single node still needs to contend with other nodes for this entire channel to be allocated which subsequently results in the problem of extra time required for contention and contention resolution if there is a collision. Moreover, contention resolution normally uses the basic and lower transmission rate option prior to the data transmission. Hence, this added time and overhead transmitted at lower rates act as a drag on efficiency as physical data rates increase.

One way to improve MAC efficiency would be to send larger frames once the channel is allocated. For example 802.11n uses frame aggregation to send multiple frames in one contention period. Unfortunately when physical data rates increase significantly, sending larger aggregated frames become impractical. For example to achieve 80% efficiency in a

300Mbps 802.11n network frames should be 23KB long [5] which is unfeasible if delay constraints are to be met.

A promising solution to the problem is channel width adaptation. It divides one large channel into several smaller channels for different users that simultaneously have data to transmit, or aggregates several small channels into one larger channel for one user with a high throughput requirement. This maximizes the functionality of the MAC layer allowing for a dynamic allocation of smaller channels according to individual throughput needs. Channel width adaptation aims to optimize throughput for end users and network efficiency at the same time. This approach makes sense for next generation wireless networks which benefits from increasing physical layer rates but will have to meet a wide range of throughput demands from different users simultaneously.

### *1.2. Recent research activities*

In 2008, Chandra and Bahl [4] used commodity 802.11 hardware to communicate at different channel widths of 5, 10, 20 and 40 MHz in order to quantify the impact of channel width on throughput, range and power consumption. Their research showed that channel adaptation can lead to significant improvements in many of the desirable metrics in wireless networks: range and connectivity, battery power-consumption and capacity. Driven by the benefits of adapting channel width according to different network scenarios, IEEE 802.11n standard [1] is enhanced by a simple channel aggregation technique: allowing end users to aggregate two adjacent 20 MHz channels into one 40MHz channel at the spectrum band of 5GHz U-NII. The main objective of this enhancement is to support high-throughput traffic. Next generation wireless networks (IEEE 802.11 ac) go further on channel bonding by increasing the maximum width from 40MHz to 80MHz or even 160MHz in order to meet throughput demands for Gigabit wireless applications.

It is clear that a tendency to bond channels to meet high-throughput demands is taking place, however the other side of the equation (i.e. accounting for a range of simultaneous lower throughput demands and providing finer granularity within channels to increase efficiency when meeting these demands) is more difficult to tackle. In order to increase network efficiency in high-density WLANs, Kun [5] introduces a method named FICA (Fine-grained Channel Access) that can allocate the spectrum resource at a thinner granularity. It utilizes OFDM to divide a whole channel into orthogonal sub-channels. It shows that when compared to traditional 802.11 channel access FICA can improve the efficiency by up to

400% [5]. Similar research work has been undertaken in Jello [6], Picasso [7] and WiFi-NC [8]. They all utilize spectrum fragmentation or channel slicing based on OFDM or OFDMA, which can slice each device's channel into separated sub-channels and thus can support concurrent and interference-free transmission over these sub-channels. The most recent work in [9] enables the operation of channel width adaptation in a more elaborate way: it allows users to adapt channel width on a per packet basis. In [10], authors propose a cooperative multi-channel MAC that enables channel width adaptation based on traffic load.

Although the stated above are lines of research in the right direction for providing dynamic channel allocation, one drawback of all methods proposed to date, including FICA, is that the sub-channels are assumed to be divided equally. This places limitations on flexibility when trying to match channel spectrum to traffic demands. There exists a research need to provide finer granularity, considering a range of channel widths, to enable the flexibility required to maximize spectrum utilization.

### *1.3. Contributions of this research*

Channel width adaptation can increase network efficiency by making use of channel bonding or by dividing the available spectrum into multiple channels, depending on traffic demand. Although multi-channel MACs have been extensively researched [11, 12], these assume that each sub-channel is divided with equal bandwidth and have identical access conditions, without considering the implications of channel width adaptation on the PHY layer. Furthermore, apart from the traditional time-domain only backoff schemes (e.g. CSMA/CA), the availability of channels at different frequencies provide a new dimension (i.e. frequency domain) to the backoff process. The potential advantages of combined time-frequency backoff schemes are not truly explored yet. To implement this approach in practice, a cross layer approach for dynamic channel adaptation (considering different width channels) is needed.

In this research, we propose a flexible cross-layer framework that enables flexible multi-channel concurrent communication and thus can fully utilize the benefit of fine-grained channel width adaptation. The proposed framework, named Sub-carrier Fine-grained Channel Access (SFCA), advances research activities in this field in the following aspects. First, the framework adapts channel width at the granularity of sub-carriers and the width of each channel can be different, while the channel width adaptation in existing work is either at the granularity of sub-channels [1, 2] or the width of sub-channels has to be the same [6-8]. This

channel adaptation with thinner granularity and more flexibility will result to a higher efficiency on wireless resource utilization. Second, the framework utilizes a combined frequency domain and time domain backoff process, which results in higher access probability and therefore less access delay for the contending nodes comparing to only backoff in frequency domain or time domain. Third, the widths of the sub-channels in the control phase can be easily adjusted and they can be different to each other, which supports a more flexible tradeoff between less access delay and more access opportunities than existing work that all the widths of the sub-channels are the same.

## 2. The Cross-layer framework

### 2.1. DOFDM for fine-grained channel width adaptation

The basic idea of channel width adaptation is that we can use variable numbers of sub-carriers, whether they are adjacent or not, to compose a channel without changing the framework of OFDM systems (as illustrated in Fig. 1). This can be easily implemented in existing algorithms and architectures, with OFDM being embraced by most recent wireless standards, such as IEEE 802.11a/g/n, WiMax and next generation Gigabit IEEE 802.11ac.

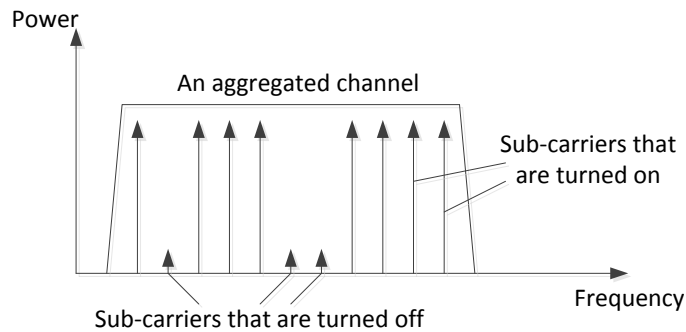


Fig. 1. Channel adaptation using DOFDM

Assuming the FFT size in OFDM modulation is  $N$  and the total available frequency bandwidth is  $B$ , the bandwidth of each sub-carrier is  $B/N$ . The framework information of OFDM, i.e.,  $B$  and  $N$ , is known to the AP and mobile terminals. We emphasize that non-adjacent sub-carriers can be aggregated into one channel and we refer to this as Discontinuous-OFDM (DOFDM). The benefit of DOFDM is twofold, first it can increase the frequency diversity, and second, it can utilize the sparse spectrum resource under the intense contention status to be experienced high-density WiFi networks.

We first consider the uplink where end users are transmitting data to the AP. A complete transmission procedure is divided into two phases, i.e. control phase and data exchange phase. During the control phase, through RTS/CTS handshake, all nodes attempt to agree on sub-carriers to be used during the following data exchange phase. In the data exchange phase, the user nodes aggregate the assigned sub-carriers into one sub-channel for data transmission. The complete data transmission procedure in its whole is illustrated in Fig. 2. Note that a sub-channel can be composed of non-adjacent sub-carriers but for convenience in Fig. 2 we illustrate a case where all sub-channels (i.e., CH 1, CH 2, ..., and CH  $M_{CH}$ ) are composed of adjacent sub-carriers. And the beacon in the beginning of the procedure is broadcasted by the AP to synchronize all the nodes in the network.

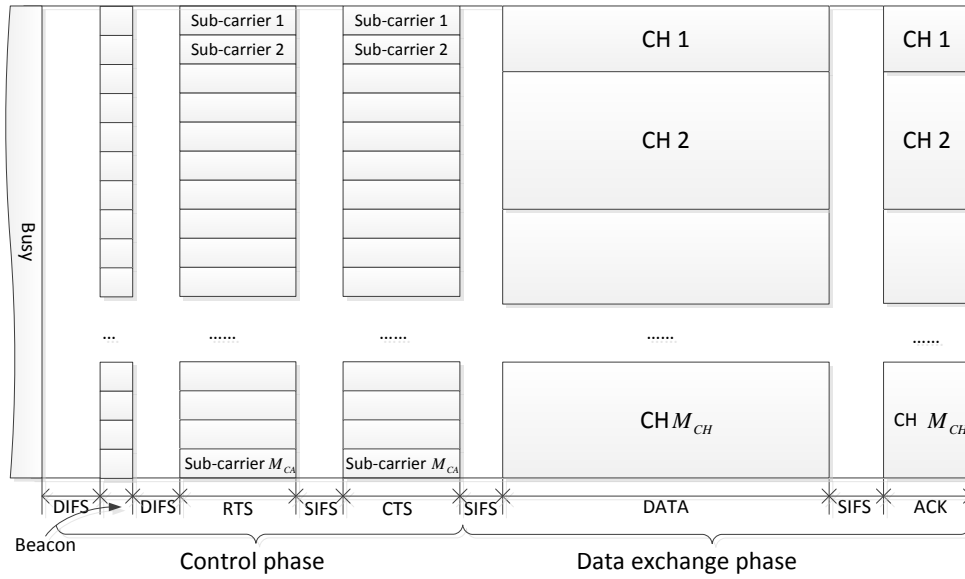


Fig. 2 Illustration of one successful data transmission procedure in SFCA

## 2.2. Packet transmission at the MAC layer

Any node that has data to transmit will select a required number of sub-carriers based on its traffic load and send this information to the AP in the RTS period. After successfully receiving the RTS's from each node, the AP will allocate the sub-carriers to the user nodes in the CTS period. The information sent in the CTS includes the IDs of the allocated sub-carriers.

When a node receives the sub-carrier allocation information, it aggregates the allocated sub-carriers as one sub-channel to transmit a DATA packet to the AP. After successfully receiving the DATA packets, the AP will send back ACKs to the transmitters using the same sub-channel used for the DATA packets. The nodes that fail to receive the ACKs from the

AP will start a re-transmission in the next transmission procedure. There is also the possibility that a node fails to obtain its requested sub-carriers during the CTS period, in which case it will perform a backoff process as explained below.

### *2.3. Frequency-time domain backoff*

There are two possible reasons why a node may fail to obtain the acknowledgment from the AP during CTS on its request for sub-carriers. First, the RTS has not reached the AP because of either a collision or physical layer impairments such as signal fading. Second, the RTS has been successfully received by the AP, but the AP has not enough sub-carriers to satisfy all nodes' request on the amount of sub-carriers, which is called sub-carrier saturation.

A novel aspect of the research presented here is to introduce a combination of frequency domain and time domain backoff process in order to tackle the two conditions described before. In the first condition, when the RTS frame was not delivered (e.g. due to a poor channel) it makes sense that the node will randomly select sub-carriers that are different to those used last time to re-send the RTS frame and thus minimize the chance of another collision or a new radio layer impairment. In the second condition where sub-carriers have become unavailable, we use time domain backoff by emulating the behavior of binary exponential backoff (BEB) used in 802.11[13]. By this method, the number of contending nodes may be reduced in the next transmission procedure, hence alleviating saturation and allowing sub-carrier availability.

A problem to be solved is how to differentiate the collision or physical layer impairment from saturation. As the AP is aware of saturation (i.e., when the RTS from a node has been successfully received but there are no more sub-carriers available) then the AP is able to inform on this situation to the relevant nodes. Otherwise, without receiving a CTS or saturation information from AP, a node concludes that its RTS has not reached the AP because of either a collision or radio layer impairment.

### *2.4. Sub-carrier allocation and negotiation*

It is worth clarifying that if the user nodes have different priorities, sub-carrier allocation will satisfy the user nodes in order of their priority. For the nodes that have the same priority, if the amount of requested sub-carriers is no more than the total available amount of sub-carriers, all the requirements will be satisfied and the AP will allocate the



number of sub-carriers specified in the nodes' request. Otherwise, the AP will have to choose its allocation strategy. For instance, to first satisfy the nodes that request more sub-carriers in order to guarantee the access to these nodes with more data to transmit, or on the contrary, to first satisfy the nodes with the smaller request in order to admit as many nodes as possible. In this paper, we propose to allocate sub-carriers to all contending nodes in the best possible fair manner according to their respective requirements, and the number of sub-carriers (denoted by  $A_i$ ) that allocated to Node  $i$  can be calculated as follows,

$$A_i = \begin{cases} d_i, & D \leq M_{CA} \\ \frac{M_{CA}}{D} \cdot d_i, & D > M_{CA} \end{cases}$$

Where  $d_i$  is the number of sub-carriers required by Node  $i$ ,  $D = \sum_i d_i$  is the total number of required sub-carriers by all the contending nodes, and  $M_{CA}$  is the total number of sub-carriers. And the detailed sub-carrier allocation algorithm is listed in Table I.

**Table I** Sub-carrier allocation algorithm

<p><b>Input:</b> The total number of sub-carriers (<math>M_{CA}</math>), the required number of sub-carriers from Node <math>i</math> (<math>d_i</math>) and its priority (<math>r_i</math>), <math>i=1, 2, \dots, n</math>, where <math>n</math> is the total node number.</p> <p><b>Output:</b> The number of sub-carriers allocated to Node <math>i</math> (<math>A_i</math>), <math>i=1, 2, \dots, n</math></p>
<p><b>Sub-carrier allocation :</b></p> <p>Calculate <math>D = \sum_{i=1}^n d_i</math> ; //The total required sub-carriers</p> <p><b>If</b> <math>D \leq M_{CA}</math> //The sub-carriers are enough to satisfy the requirement</p> <p>    <b>For</b> <math>i</math> from 1 to <math>n</math></p> <p>        Set <math>A_i = d_i</math> ;</p> <p>    <b>End</b></p> <p><b>Else</b></p> <p>    Sort <math>r_i</math> in a decreasing order and set <math>A_0 = 0</math></p> <p>    <b>For</b> <math>i</math> from 1 to <math>n</math> //To allocate sub-carriers first to the nodes</p> <p>        // with higher priority</p> <p>        <b>If</b> <math>r_i &gt; r_{i+1}</math> //Node <math>i</math> has higher priority</p> <p>            Set <math>A_i = \min\{d_i, M_{CA} - \sum_{k=0}^{i-1} A_k\}</math> ;</p> <p>        <b>Else</b> //Nodes <math>i</math> and <math>i+1</math> has the same priority</p> <p>            Find <math>m</math> to satisfy <math>r_i = r_m</math> and <math>r_i &gt; r_{m+1}</math></p> <p>            <b>If</b> <math>\sum_{k=i}^m d_k \leq M_{CA} - \sum_{k=0}^{i-1} A_k</math> //The left sub-carriers are enough</p> <p>                Set <math>A_i = d_i</math> ;</p> <p>            <b>Else</b></p> <p>                Set <math>A_i = \frac{M_{CA} - \sum_{k=0}^{i-1} A_k}{\sum_{k=i}^m d_k} \cdot d_i</math> ; //Fair allocation</p> <p>            <b>End</b></p> <p>        <b>End</b></p> <p>    <b>End</b></p> <p><b>End</b></p>

A more challenging and interesting approach would be to allocate sub-carriers considering the users' QoS as well as the adoption of adaptive coding and modulation (ACM) techniques [14]. With this approach, the amount of the sub-carriers that is required by each node may vary within a range, for instance between  $S_{min}$  and  $S_{max}$ , instead of being a fixed number. In this case, the AP will first try to guarantee the basic requirement,  $S_{min}$ , and if it has more sub-carriers it can then update the service to this node by allocating up to  $S_{max}$  sub-carriers. The settings of  $S_{min}$  and  $S_{max}$  provide greater system flexibility towards optimizing the frequency spectrum.

### *2.5. Tradeoff in the control phase*

During the control phase, each user competes for several sub-carriers to transmit the RTS frame. The AP responds with a CTS frame in the same sub-channel. There is one crucial practical issue that needs consideration. The higher the bandwidth (i.e., the more sub-carriers) that each sub-channel utilizes, the higher the transmitting rate can be obtained along one sub-channel, and therefore the shorter time for handshake, which results into less access delay. However, given the total bandwidth is fixed, the higher the width of each sub-channel the less number of sub-channels available and therefore a low number of sub-channels leads to less access opportunities for contending nodes. In contrast, following a similar reasoning, the narrower the bandwidth of each sub-channel, the more access opportunities and the longer the access delay.

For this practical consideration, a novel aspect of our framework is to dynamically adjust the number of sub-carriers contained in one sub-channel depending on the network density. In particular, when more users compete for the channel access, an RTS/CTS sub-channel with narrower bandwidth is more suitable in order to increase the access probability. While in a low density scenario with fewer users, RTS/CTS sub-channels with wider bandwidth is preferable to reduce the duration of the control phase and access delay. By dynamically adjusting the bandwidth of sub-channels based on the network density during the control phase, the potential overhead introduced at the control phase by extra delays and contention resolution can be reduced while at the same time guaranteeing sufficient access opportunities.

To obtain the information of network density, we can estimate the number of competing nodes [15] or just use a self-adaptive process based on the number of accessing

nodes in the last transmission procedure. We leave further details of this specific topic for future work.

## 2.6. Uplink vs. downlink

Downlink access follows the same process as uplink with roles reversed. The AP will use the RTS frame to send the requested sub-carriers and respective receivers' IDs, and the receivers will feedback with the CTS frames. To avoid the collision between nodes and the AP when both sides have packets to transmit, we use a similar method to that used in [5] which assigns different DIFS duration to the AP and user nodes. The side with a shorter DIFS has priority to access the channel and will send the RTS first.

## 3. Performance evaluation

### 3.1. Throughput performance

We first employ a simple scenario to validate the performance of the proposed SFCA framework using the NS2.34 simulator. We consider a wireless network where contending users are randomly deployed in an area of 250m×250m and the AP is located at the center. The packet length is subject to a uniform distribution ranging from 128 bytes to 2048 bytes. It is assumed that all users have the same packet arrival rate. Other simulation parameters are listed in Table II.

**Table II** System parameters and additional parameters used in the simulations

Parameters	Values
Minimum contention window in BEB	4
Length of RTS	44 bytes
Length of CTS	38 bytes
Length of ACK	38 bytes
SIFS	16μs
DIFS	34μs
Total PHY data rate	80Mbps
The number of sub-carriers	160
PHY data rate for each sub-carrier	0.5Mbps

Fig. 3 shows the saturated aggregate throughput varying with different numbers of contending users under 3 different cases where we divide the total bandwidth into 4, 8 or 32 sub-channels (each sub-channel has the same width) during the control phase. The figure confirms the tradeoff as explained previously that in general a higher density scenario favors

the use of more sub-channels. This is because more sub-channels provide more access opportunities and thus decrease the possibility of many nodes contending for the same sub-channel. This decrease on contention leads to less probability of collision and hence less time wasted for backoff, which results in an increase of network efficiency. For instance, as illustrated in Fig.3, under the simulated scenario, the aggregated throughput raises up to 130% when there are 55 contending nodes.

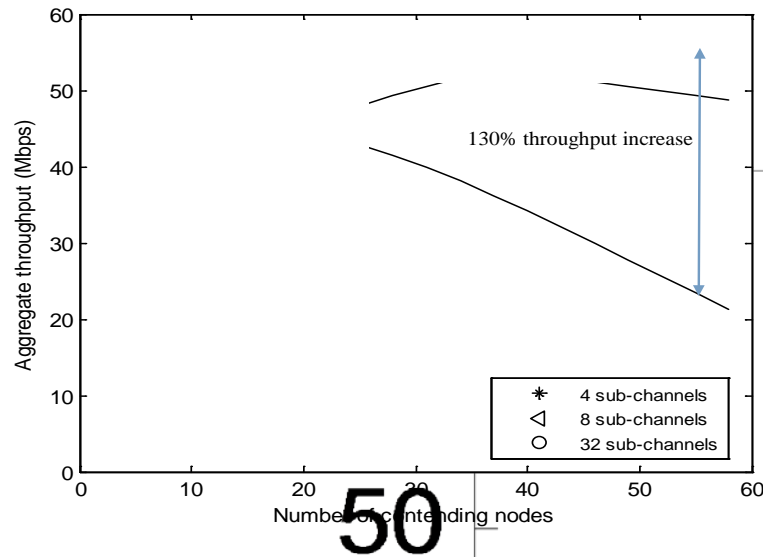


Fig. 3. The saturated aggregate throughput vs. the number of contending nodes

### 3.2. Increase of the frequency utilization efficiency: comparing with FICA

In this section, we provide a straightforward analysis to understand how SFCA can improve the frequency utilization efficiency over FICA, and then simulation results are provided to validate the analysis.

#### (i) Analysis

FICA has been well received by the research community as a scheme to provide finer granularity channel allocation [5]. FICA divides the channel into sub-channels that contain the same number of sub-carriers, i.e.,  $S = M_{CA}/M_{CH}$ , (where  $S$  is the number of sub-carriers in a sub-channel,  $M_{CA}$  and  $M_{CH}$  is respectively the total number of sub-carriers and sub-channels), and hence each sub-channel is of the same bandwidth. When a new transmission opportunity appears, a node will try to contend for a sub-channel as a whole, i.e.,  $S$  sub-carriers, via transmitting an RTS frame on a sub-carrier that is randomly selected among

those which constitute the intending sub-channel<sup>1</sup>. The probability that a node's request on a sub-channel is finally successful can be calculated as:

$$p_{suc} = p_{tx} \cdot p_{conf} \quad (1)$$

where  $p_{tx}$  and  $p_{conf}$  are respectively the probability that a node successfully sends its request to the AP and that the request is confirmed by the AP. Given that  $M_{CA} > 1$ ,  $M_{CH} > 1$ ,  $N > 1$  and all the contending nodes,  $N$ , have the same priority we have:

$$p_{tx} = \left(1 - \frac{1}{M_{CA}}\right)^{N-1} \quad (2)$$

$$p_{conf} = \left(1 - \frac{1}{M_{CH}}\right)^{N_{tx}-1} + \sum_{i=1}^{N_{tx}-1} \left[ \binom{N_{tx}-1}{i} \cdot \left(\frac{1}{M_{CH}}\right)^i \cdot \left(1 - \frac{1}{M_{CH}}\right)^{N_{tx}-1-i} \cdot \frac{1}{i+1} \right] \quad (3)$$

The first and second term in the right hand side of (3) respectively denote the probability that no other nodes are contending for the same sub-channel and that a node is selected as the winner among other nodes contending for the same sub-channel.  $N_{tx} = \lceil N \cdot p_{tx} \rceil$  indicates the number of nodes that successfully sent requests to the AP, where  $\lceil \cdot \rceil$  is the ceiling function.

Once a node succeeds in the contention phase, it will be allocated the whole sub-channel, thus the total amount of sub-carriers that are allocated to nodes by the AP is  $S_a = (M_{CA}/M_{CH}) \cdot N_{suc}$ , where  $N_{suc} = \lceil N \cdot p_{suc} \rceil$  is the number of nodes that are successfully allocated sub-channels. And denoting the set of these successful nodes as  $P$ , the number of sub-carriers that are required by them is  $S_u = \sum_{i \in P} d_i$ , where  $d_i$  is the amount of sub-carriers that are actually needed by Node  $i$ . Then the allocation ratio  $\eta_a$  and the utilization ratio  $\eta_u$  of the sub-carriers can be calculated as:

$$\eta_a = \frac{S_a}{M_{CA}} = \frac{N_{suc}}{M_{CH}} \quad (4)$$

$$\eta_u = \frac{S_u}{M_{CA}} = \frac{\sum_{i \in P} d_i}{M_{CA}} \quad (5)$$

The fundamental difference between the proposed SFCA and FICA is that SFCA allows each node to request a different number of sub-carriers, i.e.  $d_i$ . Therefore for each

---

<sup>1</sup> In FICA, only one sub-carrier is used for handshake, and therefore to provide a fair comparison, we assume that both SFCA and FICA use just one sub-carrier to send RTS in the control phase, although in reality SFCA is enabled with the adaptive tradeoff mechanism.

Node  $i$  in SFCA the amount of sub-carriers needed (i.e.  $d_i$ ) may be different, while in FICA all  $d_i$  values are the same as all nodes use the same number of sub-carriers, i.e.  $M_{CA}/M_{CH}$ .

In the proposed SFCA scheme, the amount of sub-carriers requests received by the AP is  $D = \sum_{i=1}^N d_i \cdot p_{suc}$ . If  $D \leq M_{CA}$ , the number of sub-carriers that are allocated to a successful Node  $i$  matches its request:  $A_i = d_i, i \in P$ . Else, if  $D > M_{CA}$ , the AP will allocate the total available amount of sub-carriers to the user nodes according a predefined allocation strategy. Without loss of generality, here we assume all the user nodes have the same priority and the sub-carrier allocation is proportional to their respective requests, namely  $A_i = (d_i/D) \cdot M_{CA}$ ,  $i \in P$ . In both cases,  $p_{suc} = p_{tx}$ , which can be calculated via (2), since each node that successfully sends an RTS to the AP will be confirmed by the AP. Hence the average number of allocated sub-carriers in one data transmission procedure is:

$$S_a = \sum_{i \in P} A_i = \begin{cases} \sum_{i \in P} d_i, & D \leq M_{CA} \\ \sum_{i \in P} \frac{d_i}{D} \cdot M_{CA}, & D > M_{CA} \end{cases} \quad (6)$$

Thus in our approach (as we don't allocate unnecessary carriers within a sub-channel) the allocation ratio and the utilization ratio of the sub-carriers are the same and are as follows:

$$\eta_u = \eta_a = \frac{S_a}{M_{CA}} = \begin{cases} \sum_{i \in P} \frac{d_i}{D}, & D \leq M_{CA} \\ 1, & D > M_{CA} \end{cases} \quad (7)$$

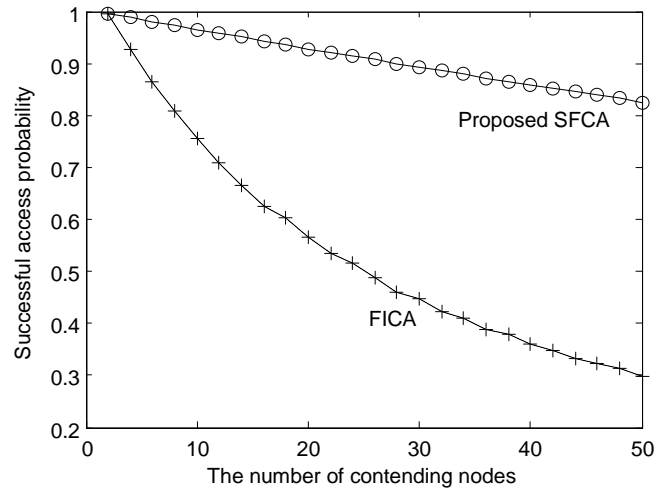
Comparing equation (7) with equation (5), it can be appreciated that the utilization ratio in SFCA is always higher than in FICA.

## (ii) Simulation results

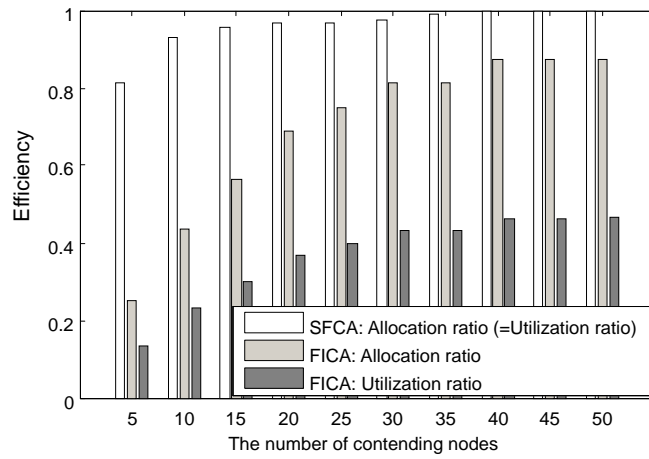
For fair comparison, we have chosen similar OFDM parameters to those considered in FICA:  $M_{CA} = 256$  and  $M_{CH} = 16$ , which means that in FICA there are 16 sub-carriers in each sub-channel. The number of sub-carriers requested by each node,  $d_i$ , is randomly selected from 1 to 16 (in practice, a node may request more than 16 sub-carriers, this meaning that it will have to contend for more than one sub-channel in FICA).

We change the number of contending nodes, i.e.,  $N$ , to change the network load and create both scenarios: when the request for sub-carriers is less and more than the total

available sub-carriers. The proposed SFCA scheme is compared with FICA as plotted in Fig. 4.



a



b

*Fig. 4. Comparing the proposed SFCA with FICA*

a the successful access probability

b the allocation ratio and the utilization ratio

From Fig. 4a, we can see that the successful access probability in the proposed SFCA scheme is much higher than in FICA resulting in more nodes accessing the AP (which also results in a higher allocation ratio as shown in Fig.4b). The reason lies in two facts: first, allowing more flexibility on the width of sub-channels in the control phase brings more access opportunities, and second, the combined time-frequency domain backoff reduces the collision probabilities even further. From Fig. 4b we can also see that the proposed scheme can bring higher frequency efficiency in terms of both allocation ratio and utilization ratio;

this is because it allocates the frequency resource in the granularity of the sub-carrier and can adapt the sub-channel width according to each node's request.

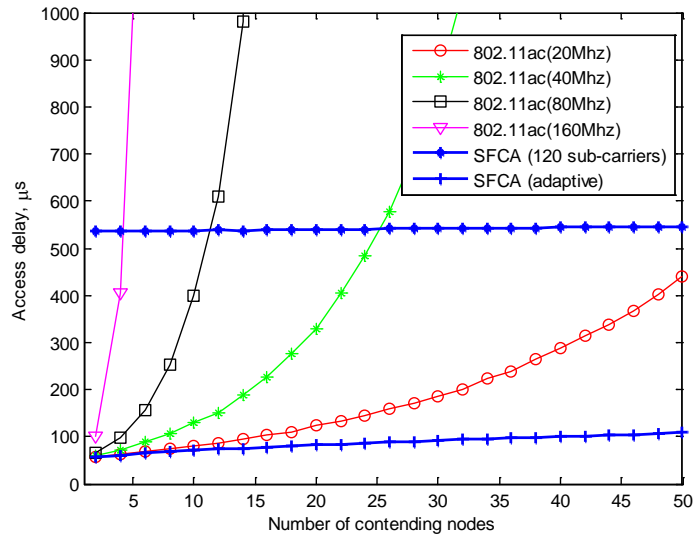
### *3.3. Adopting the framework in 802.11ac*

We have also evaluated SFCA for the upcoming IEEE 802.11ac technology. This promising technology will satisfy high throughput demands. The newly retrieved 802.11ac amendment is to significantly increase throughput (a maximum single link throughput of at least 500 Mbps) [16]. The most notable feature of 802.11ac is the extended bandwidth of the wireless channels. 802.11ac mandates support of 20, 40 and 80 MHz channels (versus 20 and 40 MHz in 802.11n). Optionally, the use of contiguous 160 MHz channels or non-contiguous 80+80 MHz channels is also allowed. However, the wider bandwidth used in 802.11ac channels and consequently the limited number of available 80 MHz channels inevitably results in more collision probability. Therefore, both: RTS and CTS (optionally) support a “dynamic bandwidth” mode. In this mode, RTS/CTS may be sent only on primary channels (i.e., half of the whole bandwidth) that are available. The proposed SFCA scheme is in accordance with the 802.11ac amendment, and the tradeoff used in the control phase (see Section II.E) can improve the “dynamic bandwidth” mode by using fine-grained channel access. In particular, the width of the primary channel in 802.11ac is at least 20 MHz, which is still considered a coarse-grained mechanism if we consider it for RTS/CTS handshake, especially in a high-density network scenario. SFCA is able to adjust the width of this handshake channel and thus greatly decrease the access delay in the control phase. In the data exchange phase, the fine-grained channel adaptation employed by SFCA can match the requirements of different users by making use of different channel widths, hence bringing a higher frequency utilization efficiency than that of coarse-grained channel bonding (which consider channels in integral multiples of 20 MHz) in 802.11ac.

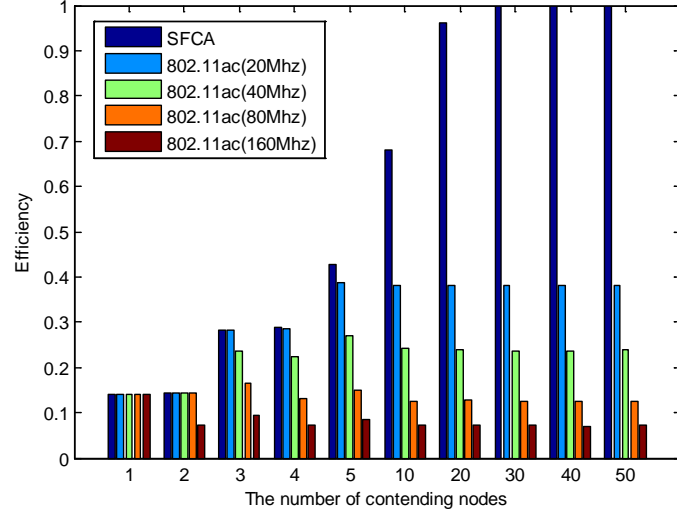
In Fig. 5, we compare the performance of 802.11ac before and after it adopting SFCA. Figure 5a presents the average network access delay, which is the average number of access attempts multiplied by the time consumed in one access attempt. To provide a fair comparison, we use frequency-domain backoff process and do not limit the number of maximum re-transmissions, namely, a failed handshake can randomly select a new sub-channel and keep trying until it accesses the AP. We evaluate the four cases of 802.11ac that use the bonded channels of 20, 40, 80 and 160 MHz. For SFCA, we evaluate two cases: (i) disabling the adaptive process by fixing the control channel used by each node as 120 sub-



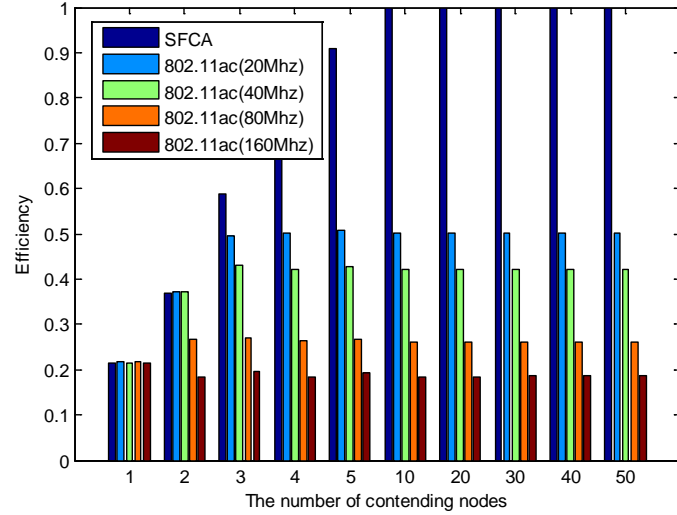
carriers, i.e., 1.8 MHz in frequency bandwidth (each sub-carrier occupies 15 KHz in frequency); (ii) enabling the adaptive process where the control channel used by each node can be adapted according to network density. We can see that the proposed SFCA can also significantly shorten the access delay in general. This is because that SFCA do not have to use the same channel width for handshake as that for transmission. Given the fixed width of total channel, the narrower each control channel is (only if the channel is robust enough for correct handshaking), the less probability that one control channel will collide with another one, and therefore it can probably shorten the average handshake process. However, under unsaturated scenarios with low number of contending nodes, narrower control no do not always bring shorter access delay. For instance under unsaturated scenarios, if we fixed the control channel width in SFCA as 1.8 MHz, the access delay is higher than 802.11ac that use the control channel with more than 20 MHz. This is because when there is little collision and thus few re-handshakes, the time consumed in one RTS-CTS handshake process using a narrower channel in SFCA will be higher than that using a wide channel in 802.11ac. This problem can be solved by enabling SFCA with the adaptive process, which adaptively changes the width of control channel according to according to the number of contending nodes. After enabling SFCA with the adaptive process, the access delay will always be kept at a very low level (below 100 $\mu$ s, as plotted in Fig. 5a).



a



b



c

*Fig. 5 Performance evaluation of SFCA in 802.11ac*

a Access delay

b the channel utilization ratio under “ordinary scenario”

c the channel utilization ratio under “high-rate scenario”

To evaluate the frequency utilization efficiency, we use two scenarios: “ordinary scenario” (where most applications are average data rate) and “high-rate scenario” (where most applications require high-rate transmission). In the ordinary scenario, we consider a video application. Since different users may require different qualities of the transmitted video, without loss of generality, we set the requested video transmitting rate as uniformly distributed from 4.5 Mbps to 15 Mbps. And considering that 802.11ac is designed to support high rate transmission, we also set that half of the contending nodes (we set a probability of

50%) will demand the much higher rate of 1Gbps. In the high-rate scenario, the requests for transmitting for all contending nodes are uniformly distributed from 100Mbps to 1Gbps. The channel band used in the simulation is 5490-5710 MHz (i.e., 220 MHz), which can be used as eleven 20 MHz channels, five 40 MHz channels, two 80 MHz channels, or one 160 MHz channel.

Figures 5b and 5c present the average results of 10000 simulations for the ordinary scenario and high-rate scenario respectively. We can observe in the ordinary scenario (Fig. 5b) that SFCA always achieves the highest channel utilization efficiency, which reaches up to 99% when the network starts getting saturated (more than 20 contending nodes), while 802.11ac achieves no more than 40% efficiency (using wider channels lead to even lower efficiency). In the high rate scenario, (Fig. 5c), SFCA efficiency reaches 99% just after 10 contending nodes, while again 802.11ac achieves much lower efficiency (50% or lower depending on the channel width). This is because in practice, most applications' requests are not an integral multiple of the sub-channel's bandwidth. For instance, a 25 MHz bandwidth request has to be responded by bonding two 20 MHz channels or one 40 MHz channel in 802.11ac, which causes 15 MHz bandwidth waste. This also leads to a second observation, that for 802.11ac the efficiency in a high-rate scenario is more than that in an ordinary scenario. The observations confirm an important fact: although 802.11ac can support a high data rate for a specific user by using a wider channel, for the consideration of frequency efficiency, 802.11ac should be somehow compatible with no channel-bonding 802.11 standards in order to serve low-rate traffic in a more efficient manner. Following this line of thought, adopting the proposed fine-grained SFCA for 802.11ac, which adapts channel in the granularity of the sub-carrier, will achieve both high throughput support and high frequency efficiency.

### *3.4. Further considerations*

Although SFCA provides flexibility, faster access and higher frequency efficiency, for its implementation some open challenges need to be discussed. First, in SFCA, we assume that all RTS/CTS handshake packets can be correctly received if there is no collision, regardless of the channel width used. However, in practice, there should be a scheme to make sure that the control channel is robust enough for correct handshake (for instance, by providing a sufficient number of sub-carriers). Second, SFCA requires each sub-carrier to be orthogonal so that guard bands are not necessary, however, if this orthogonality requirement

is not satisfied, guard bands should be considered between adjacent sub-channels. Third, the fine granularity provided for channel adaptation (including bonding and split), as well as the synchronization among sub-carriers and sub-channels, require more elaborate consideration using DOFDM. This implementation problem has been discussed in existing work [5-9], but it still needs further research in two aspects: the improvement of the synchronization accuracy and a decrease of the overhead.

## 4. Conclusions

We have presented a cross-layer framework, SFCA, which provides fine-grained channel width adaptation and multi-channel access for high-density WiFi networks. It splits one transmission procedure into a control phase and a data exchange phase. In both phases it adapts the sub-channel width in the granularity of the sub-carrier independently to provide more flexibility. Furthermore, in the control phase, the combination of time and frequency domain backoff decreases the access collision and provides less access delay for the contending nodes. The adaptive channel width based on network density supports a flexible tradeoff between less access delay and more access opportunities. In the data exchange phase, by providing fine-grained channel adaptation, SFCA achieves both high-throughput and high frequency efficiency. We have also evaluated SFCA in next generation IEEE 802.11ac networks. The basic principle of SFCA is in accordance with the “dynamic bandwidth” mode in 802.11ac. Adopting SFCA with its fine-grained channel adaptation scheme for Gigabit 802.11ac networks will achieve better performance in terms of both access delay and frequency efficiency.

We believe the flexible framework presented in this research can enhance current and future high-density, high-throughput wireless networks by increasing their efficiency.

## 5. Acknowledgments

This research is supported by National Natural Science Foundation of China (No. 61471376) and the 863 project (No.2014AA01A701).

## 6. References

- [1] “IEEE Standard for Information technology-- Local and metropolitan area networks-- Specific requirements-- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: Enhancements for Higher Throughput,” in *IEEE Std 802.11n-2009*, Oct. 29, 2009.

- [2] "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," 2012.
- [3] V. Shrivastava, S. Rayanchu, J. Yoonj and S. Banerjee, "802.11n under the microscope," In *Proc. of the 8th ACM SIGCOMM conference on Internet measurement (IMC)*, pp. 105-110, 2008
- [4] R. Chandra, R. Mahajan, T. Moscibroda, *et al.*, "A Case for Adapting Channel Width in Wireless Networks," in *Proc. of SIGCOMM*, New York, Aug. 2008.
- [5] J. Fang, K. Tan, Y. Zhang, *et al.*, "Fine-Grained Channel Access in Wireless LAN," *IEEE/ACM Transactions on Networking*, vol.21, no.3, pp.772-787, June 2013
- [6] L. Yang, W. Hou, L. Cao, *et al.*, "Supporting demanding wireless applications with frequency-agile radios," in *Proc. of USENIX NSDI*, 2010.
- [7] S. Hong, J. Mehlman and S. Katt, "Picasso: Flexible RF and spectrum slicing," in *Proc. of ACM SIGCOMM*, 2012.
- [8] K. Chintalapudi, B. Radunovic, V. Balan, *et al.*, "WiFi-NC: WiFi over narrow channels," in *Proc. of USENIX NSDI*, 2012.
- [9] S. Yun, D. Kim and L. Qiu, "Fine-grained spectrum adaptation in WiFi networks," in *Proc. of ACM Mobicom*, 2013.
- [10] C. Shi, H. Zhao, S. Zhang, D. Ma and J. Wei, "Traffic-aware channelization medium access control for wireless ad hoc networks," in *Communications, China* , vol.10, no.4, pp.88-100, 2013
- [11] J. So and Nitin H. Vaidya, "Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver," in *Proc. of MobiHoc*, 2004, pp. 222-233.
- [12] P. Kyasanur, J. So, C. Chereddi and N. F. Vaidya, "Multichannel mesh networks: Challenges and protocols," *IEEE Wireless Communications*, vol. 13, no. 2, pp. 30-36, 2006.
- [13] G. Bianchi, "Performance Analysis of The IEEE 802.11 Distributed Coordination Function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535-547, 2000.
- [14] D. O. Neill, A.J. Goldsmith and S. Boyd, "Optimizing Adaptive Modulation in Wireless Networks via Utility Maximization," in *Proc. of IEEE ICC*, 2008, pp. 3372–3377.
- [15] G. Bianchi and I. Tinnirello, "Kalman Filter Estimation of the Number of Competing Terminals in an IEEE 802.11 Network", in *Proc. of IEEE INFOCOM*, 2003.

- [16] Vivian Kelly, "New IEEE 802.11ac™ Specification Driven by Evolving Market Need for Higher, Multi-User Throughput in Wireless LANs". IEEE. Retrieved 2014-01-11.

## **Bibliography :**

### **Haitao Zhao**

Dr. Haitao Zhao received his B.S. and PhD degree in information and communication engineering both from National University of Defense Technology (NUDT), Changsha, China in 2004 and 2009, respectively. From April 2008 to July 2009 he worked as a visiting research associate in the Institute of Electronics, Communications and Information Technology (ECIT), Queen's University of Belfast, UK. He is currently an associate professor in College of Electronic Science and Engineering, NUDT. His main research interests include cognitive radio networks, self-organized networks and cooperative communications where he has published over 60 research papers. He is now a mentor member for IEEE 1900.1 standard, and a member of World-wide University Network (WUN) Cognitive Communications Consortium. And he has been involved with TPCs of IEEE ICC 2014, 2015, and several international journal editorial boards.

### **Shaojie Zhang**

Shaojie Zhang received his master degree in information and communication engineering from National University of Defense Technology (NUDT), Changsha, China in 2012. He is currently pursuing the PhD degree in School of Electronic Science and Engineering, NUDT. From 2014 to 2015, he studied as a visiting PhD student in Network Research Lab, University of Montreal. His main research interests are wireless cognitive networks and performance evaluation and optimization.

### **Emiliano Garcia-Palacios**

Dr Emiliano Garcia-Palacios is one of the leading researchers in Wireless Communications and Networks at the ECIT Institute (School of Electronics, Electrical Engineering and Computer Science at Queen's University Belfast, U.K). Over the past 20 years, he has acquired substantial expertise in the areas of Wireless Network protocols and Radio Resource

Management where he has over 70 publications. He has been involved with major research grants, conference technical programme committees and journal editorial boards. One of his main research interests is resource allocation at the medium access control layer for gigabit wireless networks and for the forthcoming Internet of Things.